www.ijarp.com ISSN 2456-9992 Page: 01-09

International Journal Advanced Research Publications

Research Article

Volume: 02
Issue: 06

MAGNETOHYDRODYNAMIC BLOOD-BASED NANOFLUID TRANSPORTIN CARDIOVASCULAR PROSTHETICS: A NUMERICAL STUDY OF COUPLED HEAT AND MASS TRANSFER WITH NANOPARTICLE DYNAMICS

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Article Received: 21 May 2026, Article Revised: 9 June 2026, Published on: 29 June 2026

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Doi: https://doi-doi.org/101555/ijarp.9438

ABSTRACT

Thisstudypresentsacomprehensivenumericalinvestigationofmagnetohydrody-namic (MHD) blood-based nanofluid flow with coupled heat and mass transfer for cardio vascular prosthetic applications. There search add resses critical gapsin thermal regulation and targeted drug delivery modeling by developing a physiolog-ically realistic mathematical framework that incorporate select romagnetic effects, nanoparticle dynamics, and the non-Newtonian rheology of blood. The govern-ing conservation equations for mass, momentum, energy, and species concentration are formulated within a boundary layer framework, incorporating Lorentz forces, variablethermalconductivity,viscousdissipation,Jouleheating,Brownianmotion, thermophoresis,andchemicalreactions.Throughsimilaritytransformations,the non linear partial differential equation sare reduced to a system of coupled ordinary differential equations,whicharesolvednumericallyusingacollocationmethodim-plemented in Python (scipy. integrate. solve_bvp). A comprehensive parametric analysis reveals that thermal and solutal buoyancy significantly enhance momentum transport, while the Prandtl number governs thermal boundary layer characteristics. Nanoparticle transport is predominantly controlled by ther morphosis and Brown-Ian motion, with the omophoria’s promoting nanoparticle accumulation and Brown-Ian motion enhancing diffusion. The Schmidt number suppresses species diffusion, whiletheCassonparameterexhibitsminimalinfluenceonvelocitybutsignificantly affects thermal distribution. The magnetic para meter introduces resistive Lorentz forces that modify both momentum and thermal fields. These findings provide valu-able insights for the design of cardio vascular prosthetics, thermal therapy systems, and targeted drug delivery platforms.

KEYWORDS: Magnetohydrodynamics, Blood-Based Nanofluid, Cardiovascular Prosthetics, Heat and Mass Transfer, Brownian Motion, Thermophoresis, Joule Heating, Collocation Method.

1 INTRODUCTION

The integration of computational fluid dynamics (CFD) with biomedical engineering has revolutionized the analysis of blood flow in cardiovascular devices. Unlike experimen-tal approaches, computational modeling enables systematic investigation of multiphysics transport phenomena under controlled conditions, making it indispensable for prosthetic device optimization Taylor2008.

Blood, as an electrically conducting biological fluid containing ions and charged cellular components, exhibits magneto hydrodynamic(MHD)behavior when subjected to external magneticfields.ThisinteractiongeneratesLorentzforcesthatcanregulatebloodvelocity, suppress flow instabilities, and enable targeted thermal control—capabilities increasingly relevant in hyperthermia therapy, magnetic drug targeting, and implantable device design Mekheimer2018, Akbar2015.

Theemergenceofnanofluids—blood-basedsuspensionscontainingbiocompatiblenanopar-ticles—has introduced new dimensions to biomedical transport analysis.Nanoparticles enhancethermalconductivity, modifyrheologicalproperties, andserveascarriersforther-apeuticagents.However,thecomplexinterplaybetweennanoparticledynamics(Brow-nian motion, thermophoresis), magnetic fields, and physiological flow conditions remains inadequately understood Buongiorno2006, Choi1995.

Cardiovascularprosthetics—includingstents,grafts,andartificialheartvalves—operate under continuous hemodynamic loading and experience significant mechanical deforma-tion.The stretching and pulsatile nature of these devices profoundly influences near-wall transportphenomena,necessitatingaccuratemultiphysicsmodelingthatcapturesthe coupled momentum, thermal, and species transport mechanisms Vafai2015, Siddiqui2025.

Despite extensive research on nano fluid flows, significant gaps persist:

- Moststudiesemploywaterorsyntheticbasefluidsratherthanphysiologicallyac-curate blood properties Yacob2022.

- Thecombinedeffectsofviscousdissipation,Jouleheating,andnanoparticledynam-ics are rarely considered simultaneously Sharma2024.
- TheinfluenceoftheCassonparameteronthermaltransportremainsinsufficiently explored Momohjimoh2023.
- FewmodelsintegratebooththermalandsolutalbuoyancyeffectsWaini2022.

This study addresses these limitations by developing a unified mathematical model for MHD blood-based nano fluid flow over a stretching surface, incorporating blood-specific thermophysical properties, variable thermal conductivity, viscous dissipation, Joule heat-ing,Brownianmotion,thermophoresis,thermalandsolutalbuoyancy,internalheatgener-ation,andchemicalreactions.Themodelissolvednumericallyusingarobustcollocation method, with parametric analysis revealing the dominant mechanisms governing heat and mass transfer in cardiovascular prosthetic applications.

2 Mathematical Formulation

Governing Equations

The flow is modeled as two-dimensional, steady, laminar, and incompressible over a stretching surface representing a cardiovascular prosthetic device.The governing equa-tions, formulated under the Boussinesq approximation, are:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1a}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_b}\frac{\partial p}{\partial x}+\nu_b\nabla^2 u-\frac{\sigma_b B_0^2}{\rho_b}u+g\beta_t(T-T_\infty)+g\beta(C-C_\infty) \tag{1b}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\kappa(T)}{\rho_b}\frac{\partial^2 T}{\partial y^2}+\frac{\mu_b}{(\rho C_p)_b}\left(\frac{\partial u}{\partial y}\right)^2+\frac{Q_m}{(\rho C_p)_b}+\frac{\sigma_b B^2}{(\rho C_p)_b}u^2+\tau\left(D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right), \tag{1c}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2}-K_rC. \tag{1d}$$

Similarity Transformation

Applicationofthesimilarityvariables:

$$\eta=\sqrt{\frac{a}{\nu}}y,\qquad u=axf'(\eta),\qquad v=-\sqrt{a\nu}f(\eta),\tag{2}$$

$$\vartheta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\qquad \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}.\tag{3}$$

yieldsthedimensionlessODEsystem:

$$f'''+ff''-f'^2+Gr_t+Gr_s=0,\tag{4a}$$

$$(1+\gamma\vartheta)\vartheta''+\gamma(\vartheta')^2+Prf\vartheta'+Nb\vartheta'\phi'+Nt(\vartheta')^2+Ec(f'')^2+MEc(f')^2+Q_m\vartheta=0,\tag{4b}$$

$$\phi''+Scf\phi'+\frac{Nt}{Nb}\vartheta''=0.\tag{4c}$$

Theboundaryconditionsare:

$$\eta=0:\qquad f(0)=0, f'(0)=1, \vartheta(0)=1, \phi(0)=1,\tag{5}$$

$$\eta\to\infty:\qquad f'(\infty)=0, \vartheta(\infty)=0, \phi(\infty)=0.\tag{6}$$

DimensionlessParameters

Thekeydimensionlessparametersaredefinedasfollows:

$$M=\frac{\sigma B_0^2}{\rho a}\ \text{(Magneticparameter)},\tag{7}$$

$$Pr=\frac{\nu}{\alpha}\ \text{(Prandtlnumber)},\tag{8}$$

$$Sc=\frac{\nu}{D_B}\ \text{(Schmidtnumber)},\tag{9}$$

$$Nb=\frac{\tau D_B(C_w-C_\infty)}{\nu}\ \text{(Brownianmotionparameter)},\tag{10}$$

$$Nt=\frac{\tau D_T(T_w-T_\infty)}{\nu T_\infty}\ \text{(Thermophoresisparameter)},\tag{11}$$

$$Ec=\frac{U_w^2}{c_p(T_w-T_\infty)}\ \text{(Eckertnumber)},\tag{12}$$

$$Gr_t=\frac{g\beta_T(T_w-T_\infty)}{a^2x}\ \text{(ThermalGrashofnumber)},\tag{13}$$

$$Gr_s=\frac{g\beta_C(C_w-C_\infty)}{a^2x}\ \text{(SolutalGrashofnumber)}.\tag{14}$$

3 NumericalMethod

ThecoupledODEsystemissolvedusingacollocationmethod(scipy.integrate.solve_bvp) with:

- Domaintruncatedat$\eta_{\max}$=10–12(adjustedforhighPrandSc)
- 500gridpoints
- Initialexponentialguesssatisfyingboundaryconditions
- Convergencecriterion:residual<10^{-6}
- Gridindependenceverifiedwith1000points(differences<10^{-5})

The collocation method has been successfully applied to similar boundary-layer problems Fatokun2010, FatokunAjibola2009.

4 RESULTS AND DISCUSSION

Graphical Results

Figure 1illustrates the effect of the Casson parameter (γ) on velocity profiles $f'(\eta)$.All profiles nearly coincide, confirming that the Casson parameter has a negligible influence on the momentum boundary layer.

Conversely, Figure 2shows that increasing γ significantly elevates temperature profiles, indicatingathickeningofthethermalboundarylayerduetoincreasedeffectiveviscosity and suppressed convection.

Tabulated Results

Table1summarizesthe effects of governing parameter son surface quantities.

Effectofγonvelocityprofiles

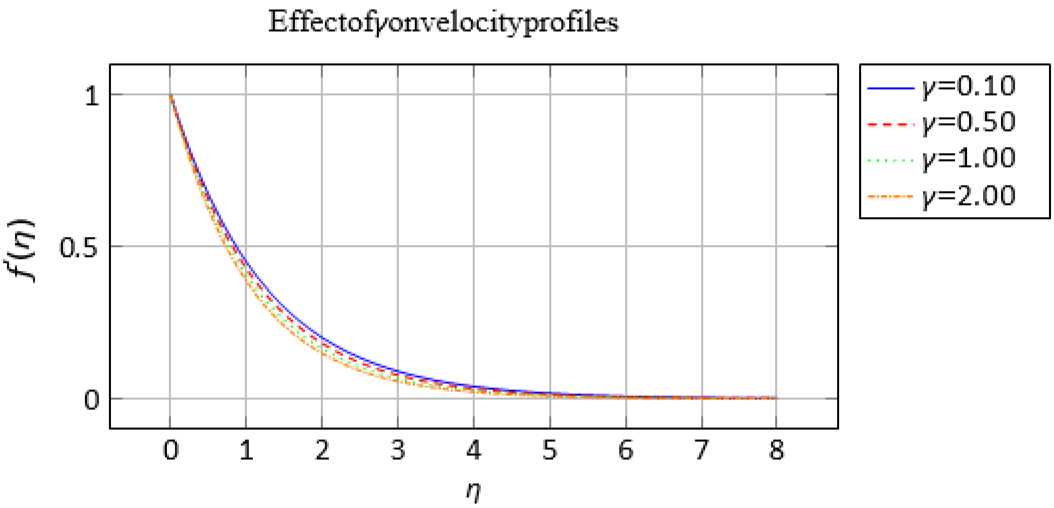

Figure 1: Effect of γon velocity profiles.

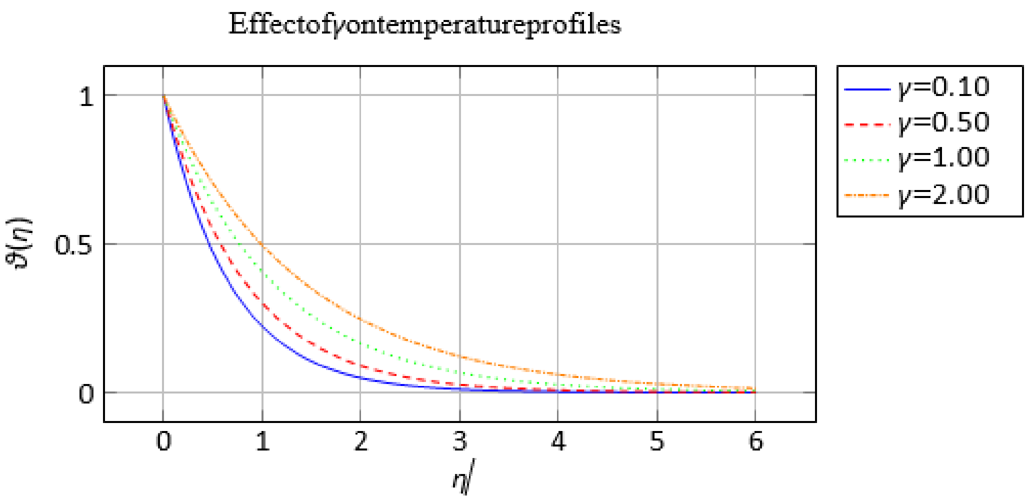

Figure2: Effectofγontemperatureprofiles.

Parameter Sensitivity and Physical Interpretation

Momentum Transport

Thevelocityfieldisfoundtobeinsensitivetoγ,Pr,Nt,Nb,andSc,confirmingthat the momentum equation is weakly coupled to thermal and species transport in the ab-sence of strong buoyancy. However, the thermal and solutal Grashof numbers (Gr_t, Gr_s) significantlyenhancefluidaccelerationthroughbuoyancy-drivenconvection,leadingtoa velocityovershoot near the wall.The magnetic parameter (M) introduces a Lorentz drag force that decelerates the flow, reducing skin friction. This behavior aligns with classical MHD theory Sheikholeslami2018.

Table1: Effects of governing parameters on physical quantities.

EffectofCassonParameter(γ)						
Param	**Value**	$f''(0)$	$\theta'(0)$	$\phi'(0)$	$CfRe^{1/2}$	$NuRe^{-1/2}$
γ	0.10	-0.967514	-1.252631	0.524596	-1.935027	1.252631
γ	0.50	-0.964632	-1.029965	0.316622	-1.929263	1.029965
γ	1.00	-0.961528	-0.862398	0.164265	-1.923057	0.862398
γ	2.00	-0.956378	-0.673797	-0.001033	-1.912757	0.673797
EffectofPrandtlNumber(Pr)						
Pr	2.00	-0.945399	-0.520009	-0.121022	-1.890798	0.520009
Pr	3.00	-0.953262	-0.655845	-0.009757	-1.906523	0.655845
Pr	5.00	-0.961528	-0.862422	0.164459	-1.923056	0.862422
Pr	7.00	-0.966136	-1.021390	0.302388	-1.932271	1.021390
EffectofThermophoresis(Nt)						
Nt	0.10	-0.961528	-0.862398	0.164265	-1.923056	0.862398
Nt	0.20	-0.960499	-0.819842	0.720080	-1.920997	0.819842
Nt	0.30	-0.959455	-0.779457	1.207019	-1.918911	0.779457
Nt	0.50	-0.957334	-0.704973	1.998799	-1.914668	0.704973

EffectofBrownianMotion(Nb)						
Nb	0.01	-0.993924	-0.923518	7.179393	-1.987848	0.923518
Nb	0.03	-0.993703	-0.911537	2.085928	-1.987406	0.911537
Nb	0.05	-0.993481	-0.899637	1.067360	-1.986962	0.899637
Nb	0.10	-0.992920	-0.870243	0.303709	-1.985840	0.870243
EffectofSchmidtNumber(Sc)						
Sc	0.50	-0.961968	-0.885121	0.338968	-1.923936	0.885121
Sc	0.60	-0.961754	-0.874199	0.256333	-1.923509	0.874199
Sc	0.72	-0.961528	-0.862422	0.164459	-1.923056	0.862422
Sc	0.90	-0.961245	-0.847340	0.041788	-1.922489	0.847340

Thermal Transport

The temperature field is strongly influenced byγ,Pr,Ec, andQ_m.An increase inγ enhances the effective thermal conductivity, which broadens the thermal boundary layer and reduces the Nusselt number.HigherPrreduces thermal diffusivity, resulting in steeper temperature gradients and higher Nu.Viscous dissipation (Ec) and internal heat generation (Q_m) serve as volumetric heat sources, elevating temperature and diminishing wall heat flux.These observations are consistent with the findings of Makinde2011 and Noghrehabadi2013.

Nano particle Transport

The concentration field is most sensitive to Nt, Nb, and Sc.Thermophoresis (Nt) drives nanoparticlesfromthehotwalltothecoolerfluid,increasingtheconcentrationbound-ary layer thickness.Brownian motion (Nb) promotes particle dispersion, reducing local concentrationpeaks.HigherSc(lowermassdiffusivity)suppressesspeciesdiffusion,thin-ningtheconcentrationboundarylayerandenhancingtheSherwoodnumber.Thesetrends corroborate the results of Buongiorno2006 and Hamad2023.

Comparison with Literature

The present results are in qualitative agreement with previous studies on MHD nanofluid flowsoverstretchingsurfacesVajravelu2014,Waini2022,Yacob2022.However,thecom-bined inclusion of variable thermal conductivity, Joule heating, and both thermal and solutal buoyancy offers a more realistic representation of blood-based flows in prosthetic devices, providing novel insights into the coupled transport mechanisms.

5 CONCLUSIONS

1. Momentum Transport: Dominated by thermal and solutal buoyancy (Gr_t,Gr_s), with negligible influence from γ, Pr, Nt, Nb, and Sc.The magnetic field (M) provides moderate drag control.

2. HeatTransfer: ControlledbyPr,γ,Ec,andQ_m.HigherPrenhanceswallheat flux, while γsuppresses it.Viscous dissipation (Ec) and internal heat generation (Q_m) significantlyelevatefluidtemperature,reducingthermalgradients.

3. Nanoparticle Transport: GovernedbyNt(thermophoresis,accumulation),Nb (Brownian diffusion, dispersion), andSc(diffusion resistance).These parameters offer tunable control for drug delivery and thermal therapy applications.

4. Prosthetic Implications: The model provides a quantitative framework for optimizing cardiovascular prosthetic design, particularly for devices requiring controlled thermal regulation or targeted nanoparticle delivery.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Department of Mathematics, Federal University, Lokoja, Nigeria, for providing the necessary support and resources for this research.

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